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The architecture and business value of a semi-cooperative, agent-based supply chain management system

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Abstract

Multi-agent systems have the potential to improve supply chain management. The adoption of such systems has been limited, as their design often neglects existing organizational realities and the business value for the various stakeholders is not clear. In this paper, a multi-agent system improving supply chain management is designed and its business value is evaluated. We present the semi-cooperative architecture and evaluate the benefits using agent-based simulation. We found that the multi-agent system increases the level of flexibility in the supply chain and enables supply chain members to become more responsive. This has a positive impact on the ordering lead-time, human processing time, the inventory levels and number of stock-outs.

Keywords: Multi-agent systems; Supply chain management; Evaluation; Business value; Simulation; Information architecture; Coordination

1. Introduction

Many IT applications have been employed to rationalize and optimize supply chains [19]. The rapid developments in the field of agent-based systems offer new opportunities for the management of supply chains. Supply chain performance can significantly benefit from decision-making processes that constantly monitor changing conditions and dynamically evaluate viable trading and operational options in light of these conditions [1]. As the complexity and size of supply chains increase, organizations are finding it more difficult to build systems supporting the coordination of activities performed by the independent supply chain members. Agent-based systems could provide a solution to this problem, as they provide the opportunity to construct a large, complex system out of relative simple, autonomous parts [11].

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The adoption of agent-based supply chain systems for use in practice has been limited so far. Many firms carefully watch the developments, but are reluctant to commit serious trading volumes [7].

Agent-based technologies are largely untested in practical situations [1]. Developments have suffered from a mismatch between existing organizational reality and theoretical mechanism design often focused on optimizing one aspect [9,17]. Design decisions are of crucial importance as they determine the supply chain structure-influencing inventory holding strategies, the number of transports, lead-times, stock-outs, responsiveness, liquidity, and volatility. Apart from this mismatch, decision-makers are reluctant to introduce multi-agent system (MAS) because they do not understand the possibilities of such systems in relation to the potential advantages and sources of value [4,7]. Moreover, the prospect of delegating routine supply chain decisions to software agents still makes many managers nervous [1].

Empirical research evaluating the business value of multi-agents system is limited. The benefits often remain rather abstract or even vague, are not quantified and are not derived in a structured and systematic way. The aim of this paper is twofold: (1) to design a MAS improving the coordination within a supply chain and satisfying the organizational requirements and (2) to evaluate the business value of the system. We do this by designing a semi-cooperative, agent-based supply chain management system using action research and by determining the business value of the system by comparing the performance with and without the system using agent-based simulation. This should contribute to theory formulation about the benefits of agent-based systems and semi-cooperative mechanisms and also support practitioners to decide whether or not to implement agent-based systems.

2. Related research

2.1. Agent-based systems

Software agents are often considered as very suitable for coordination the complex interdependencies between activities of independent organizations forming supply chains (e.g. [1,24]). Agents can act on behalf of a supply chain member by making use of their autonomous characteristic and decision-making capabilities. Many different definitions of software agents can be found in the literature, e.g. [2,18,23]. There is a truly heterogeneous body of research and there is no generally accepted definition of the term software agents. In general, software agents help people with time-consuming activities [18]. Inherent are the notions of problem solving capabilities, delegation and autonomy.

A MAS consists of a number of software agents cooperating autonomously within a distributed environment. In MAS, each agent is usually assigned a separate problem or part of a problem. A problem is decomposed into sub-problems and each sub-problem is assigned to a specific agent having corresponding competencies. Multi-agent systems try to solve the entire problem by collaboration with each other. In this way, MAS can help to solve complex problems and make decisions or support humans to make decisions. Agents are especially suitable for coordination supply chains due to the following characteristics:

1. Data, resources and control over data and resources are inherently distributed. Supply chain partners have their own goals, interests and requirements. There is no single authority, however, there can be a coordinator orchestrating the supply chain [8].
2. A supply chain consists of autonomous cooperating systems. Decision-making requires multi-party negotiation and coordination.
3. The management of supply chains consists of interactions between humans, humans and information systems and information systems. Often legacy systems are part of the supply chain.
4. A supply chain is adaptive and changes over time. New organizations might become involved and other might disappear.

Agents can serve as wrappers for the supply chain management components owned by a particular supply chain entity [13,14,27]. An entire company or a single department or function can be wrapped. The advantage of this approach is that the supply chain can be composed of existing (legacy) systems and new systems.

2.2. Semi-cooperative coordination

A supply chain management system should be aimed at coordinating the activities performed by independent organizations in order to improve the overall performance of the supply chain and by taking into account the individual interests and requirements of the supply chain members. Coordination mechanisms should ensure a proper balance between objectives and constraints of both individual companies and the overall performance of the supply chain. Most coordination models regard logistics management as an auction in which each entity tries to maximize its own profits (e.g. [27,32,34]) or have a cooperative nature (e.g. [3,16,17]).

Competitive approaches are aimed at optimizing one mutually exclusive goal and involve competition among stakeholders. Cooperative mechanisms are often referred to as win–win mechanism. It is often described as a decision-making process of resolving a conflict involving two or more parties over multiple, interdependent, but non-mutually exclusive goals [16].

Within supply chains, suppliers and consumers have their own selfish goals, but also the common goal of creating an efficient and effective supply chain. As a result current research on mechanism design focuses on developing semi-cooperative mechanisms, where agents strive to reach a fair and reasonable agreement for all parties [17]. Such approaches are aimed at optimizing supply chains and which nevertheless maximizes single organizations payoff.

Different semi-cooperative coordination mechanisms are appropriate under different circumstances [34]. It is often argued that mechanisms need to be developed to accommodate the special needs for a certain environment (e.g. [12,31]). Sadeh et al. [27] distinguish between horizontal and vertical coordination protocols. Horizontal or lateral coordination protocols support interactions between peer-levels agents, whereas vertical coordination protocols support interactions between agents in different layers of the hierarchy. Horizontal and vertical coordination might demand different kinds of mechanisms having different degrees of competitiveness. Cavalieri et al. [3] introduce two kinds of agents: structural and functional agents. The first kind of agents represents actors in the supply chain, the second represents function and processes, like manage information, make decisions and so on.

Julka et al. [13,14] propose a unified framework for modeling, monitoring and managing supply chains. Their framework is made up of object modeling of supply chain flows and agent-based modeling of supply chain entities. Their framework uses three classes of agents: (1) emulation; (2) query and (3) project agents. Emulation agents model the supply chain entities such as production and sales departments. Query agents handle queries from users and assists in supply chain analysis. Project agents coordinate other agents to solve a problem.

2.3. Business value of agent-based systems

There are great benefits and saving to be gained by making use of agent-based systems for supply chain management. Maes [18] argues that agents help people with time-consuming activities. Parunak [25] describes the advantages based on four distinguished characteristics of agent-based systems: (1) the identification of an agent with a particular entity; (2) decision-making capabilities are distributed over a number of autonomous actors; (3) systems of agents can change during their life-cycle by adding and removing agents; and (4) agents are suitable to deal with a number of different situations. Lange and Oshima [15] provide an overview of benefits for mobile agents. Agents: (1) reduce the network overload; (2) overcome network latency; (3) encapsulate protocols; (4) execute asynchronously and autonomously; (5) adapt dynamically; (6) are naturally heterogeneous both from hardware and software perspectives; and (7) are robust and fault-tolerant. Wagner et al. [33] found that agents increase the level of flexibility in the chain and enable supply chain members to be more responsiveness through producer/consumer negotiation and reasoning about manufacturing availability, raw material requirements, and shipping time requirements. Nissen [24] explored the application of agent technology for supply chain integration in the US government and found that agents are of crucial importance for creating speedy and responsiveness processes. Mangina et al. [19] argues that the efficiency might be increased through the elimination of unexpected mistakes, flexibility increases by lowering order quantities and supply lead-times, information visibility and information quality improves, excessive inventory and severe delays will be reduced, capacities will be balanced and customer service will be improved by pre-processing and filtering of information.

The main benefits of agent-based systems are focused on creating more effective and efficient operations and the creation of responsive systems based on real-time information sharing and decision-making. The benefits found in the literature often concern assumed benefits at a rather abstract level and are not quantified. There is no proof of the benefits in relationship to a developed system.

Agent-based systems support the fullest range of organizational activities and processes and are adopted with the aim of achieving substantial savings. Therefore, at a high-level the benefits of agent-based systems will be similar to the benefits of all enterprise systems, as given by Shang and Seddon [29]. The business value of agent-based systems is likely to be multidimensional and will cover a large number of facets. To avoid the identification of too abstract and too vague benefits, it is necessary to relate benefits directly to an agent-based system. None of the research discussed before provides a comprehensive view of an agent-based system and evaluated the benefits in a structured and systematic way.

3. Research approach

This paper describes the architecture of agent-based system and evaluates the business value of the system. The architecture of the agent-based system was designed using action research, which is focused on 'how to' questions [1]. Instead of taking the observer's point of view, the researcher is a participant. The researcher observes, as is the case with case study research, and also gets involved in theory application and the testing of improvements. In this research, the researcher facilitated the requirement elicitation process and performed the evaluation of the business value. Many other people were involved in the design of the system, including IT experts, supply chain experts and employees of the organizations involved in the supply chain. Participation is necessary, as no single person possesses all the knowledge and information required, and the solution is a 'negotiated' solution. Solutions to problems require interdisciplinary knowledge and skills and consideration of current industry practices [31]. The solution found is not optimal in some respect; instead the solution is negotiated to satisfy the different requirement and to deal with the sometimes-opposing requirements of the stakeholders.

Our research approach is based on the problem solving process to handle the design of organizational change that consists of five activities [21,30]. The problem solving cycle ensures that the existing organizational realities are taken as a starting point. The following steps were carried out:

1. Analysis, modeling and specification of the 'as is' situation.
2. Diagnosis of the 'as is' situation.
3. Solution finding, designing the architecture and multi-agent system.
4. Evaluating of the 'to be' solution, i.e. the agent-based system.
5. Selection and implementation.

Agent-based simulation is used to evaluate the benefits of the agent-based system prior to implementation. In spite of the fact that agents form the basis of both agent-based simulations and multi-agent systems, there are several differences [10]. In agent-based simulations, the agents are interacting in a simulated environment, where modeling reductions have been applied to the behavior of the environment. Furthermore, the simulator provides an artificial time mechanism that allows the agent-to-agent and agent-to-environment interactions to take place (much) faster than in reality. By placing the agents in an agent-based simulation, it becomes possible to study the system and the benefits over a prolonged period of time.

Both the current situation and the situation with an agent-based system were simulated, as we need the values of the performance indicators for the ‘as is’ situation as a ‘yardstick’ for comparison with the ‘to be’ situation. The performance differential between the situation with and without an agent-based system can be seen as a measure for the quantifiable business value. We also interviewed a number of practitioners involved in the design process to gain insight into their perceptions in order to measure the non-quantifiable business value.

4. Case study background

A case study of a retail supply chain was investigated. This supply chain delivers food, healthcare and nursery products to supermarkets and consists of three manufacturers, a central warehouse, 20 distributors, a large number of carriers and many supermarkets. There is one large supermarket chain having considerable negotiation power and there are many small, independent supermarkets having limited bargaining power.

The central warehouse decouples the production based on forecasts from the delivery based on customer demand. Each organization holds inventory, has its own decision-making rules and has other goals such as minimizing inventory levels or maximizing service levels. The following unique features requiring a semi-cooperative, agent-based supply chain management system characterize the retail chain:

1. Data and resources are distributed over many heterogeneous kinds of actors having their own goals, interests and requirements.
2. Product quality requires traceability and continues monitoring of perishable products.
3. There are a number of large demand variations during holiday periods.
4. The stores and consumers are diverse and geographically dispersed.

Products are produced in the factory and transported to a central warehouse or distribution center (DC) as shown in Fig. 1. The supply chain is decoupled at the DC; products are manufactured on stock based on demand forecasts, and products are delivered from the DC to the dealers and supermarkets based on customer orders.

Each factory has a number of product lines that can produce a particular kind of product. From

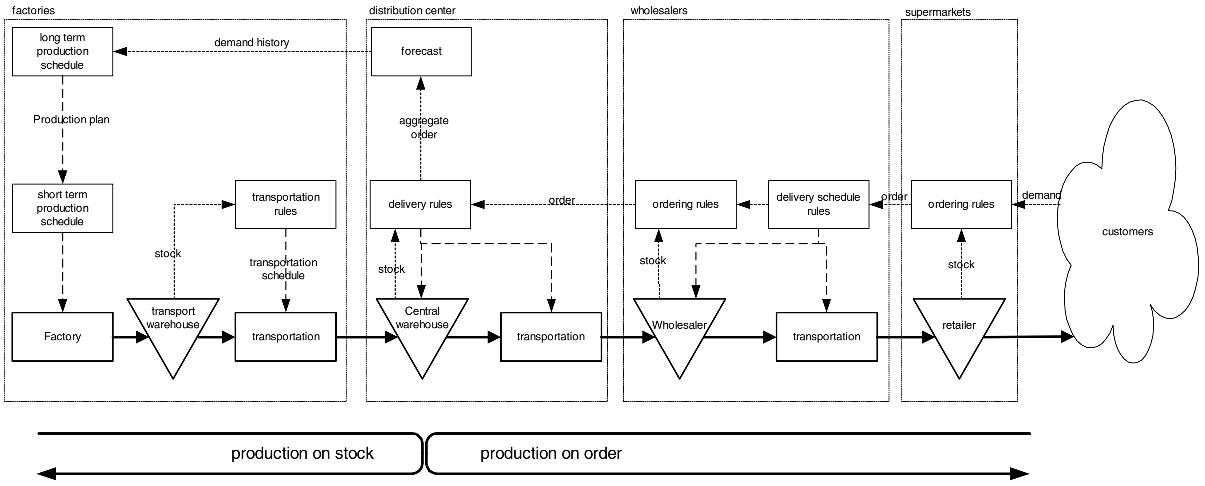

Fig. 1. Overview of the supply chain.

the central warehouse the products are distributed to wholesalers who ship the products either directly or indirectly to supermarkets. The wholesalers and supermarkets are located in different zones: a central zone, an outer zone and the islands. For each zone, there are different lead-times, replenishment frequencies and transport characteristics. In general, inventory is replenished once a week.

The supply chain under study has 50 different product families, each having its own characteristics and demand patterns. Each product family consists of a number of products, which have similar characteristics. In total there are about 300 products categories into 50 product families. The products are classified using a classification into A, B and C products (e.g. [26]). The A product class contains fast-moving products having a low value. The C product class involves slow-moving products having a high value and B is the intermediate class. The size of products may vary and consequently the number of products that can be packed within a container or pallet varies.

The DC has reserved space for storing 10,000 pallets. The DC has to pay for the space, and is able to expand the number of pallets at costs much higher than the costs of the reserved space. The DC functions as a decoupling point – a storage or repository – where different processes are decoupled. A decoupling point is used to simplify or decouple supply and demand. The holding of inventory decouples a demand-driven process (pull) from a production on stock based process (push). The production on stock is based on forecasted demand and the demand-driven part is based on the real demand. The decoupling point is visualized at the bottom of Fig. 1 and helps to deal with conflicting requirements. The decoupling point at the DC is used to reduce the complexity of coordination decisions as the activities before and after the decoupling point can be treated independently.

Third parties transport the products from the factories to the DC, from the DC to the wholesalers and from the wholesalers to the supermarkets. The capacity reserved for transportation is based on long-term contracts between carriers and shippers. The transportation capacity can also be expanded; however, additional capacity is much more expensive than the reserved capacity. Each actor in the supply chain performs a stock keeping function. The total stock keeping per actors consist of the following elements:

- Cycle stock is required for overcoming the time period between replenishments.
- Quality assurance stock is necessary for providing inspectors a sample of the product in order to test the product quality.
- Safety stock is used for protection against uncertainties in demand or lead-time.
- Contingency stock is necessary for dealing with seasonal fluctuations.

The current inventory levels and number of stock-outs are found to be too high by the organizations. On the one hand there seems to be enough inventory in the whole supply chain. On the other hand inventory seems not available at the right node in the chain. This resulted in a large number of stock-outs, especially during holiday periods, like Christmas and Easter. The organizations found that there was a need for a more flexible allocation of inventory to increase the responsiveness of the supply chain. A constraint was that the number of transports should not be increased. It is often advocated that the adaptivity of a supply chain can be increased by making use of an agent-based system (e.g. [15,33]). Therefore, the supply chain participants were looking for an architecture fulfilling their individual requirements and aimed at creating an efficient and responsiveness supply chain.

5. Architecture of the agent-based system

During the requirements elicitation process the participants decided to use a combination of the structural and functional agents proposed by Cavalieri et al. [3] and to use vertical and horizontal coordination proposed by Sadeh at al. [27] as the basis for the architecture. The participants found that adopting these concepts enables the agent-based system to stay close to the existing organizational realities.

The vertical coordination model is based on aggregation and hierarchy. All the agents have the same purpose, however, are operating at a different level in the hierarchy. Higher-level agents determine the constraints for lower-level agents. The inventory-holding policies of the inventory control agents are based on methods of statistical inventory control (e.g. [26]) and modified based on the experiences of the logistic planners of the organizations in the supply chain.

Each organization is represented using a structural agent. The structural agents can be viewed as a collection of functional agents. Only structural agents of various companies interact with each other. The architecture of the semi-cooperative coordination model was developed and is depicted in Fig. 2. The architecture is agreed on by the various stakeholders and defines the interfaces between the agents. Please note that the dealer and supermarket have the same structure and are therefore only shown once in the figure. The architecture gives freedom to each organization to add the behavior for each of the agents. As such, agents having the same name and interface but belonging to different organizations can have complete different logic. The advantage of using such a coordination structure is that the behavior within agents can easily be changed. Moreover, a wrapped (legacy) system or even human beings can perform the behavior.

There are three aggregate types of structural agents in the supply chain.

1. *Production agents* have the goal to optimize their production planning and resource utilization.
2. The *Warehouse*, *DC or intermediating* agents have the goal to balance supply and demand, negotiate with the supply and demand agents and minimize the inventory and number of stock-outs for the whole supply chain.
3. *Dealer of supermarket agents* have the goal to maximize customer satisfaction by minimizing their own number of stock-outs.

Whereas the production and dealer/supermarket agents are selfish, the DC agent aims at optimizing the supply chain. The DC acts as a kind

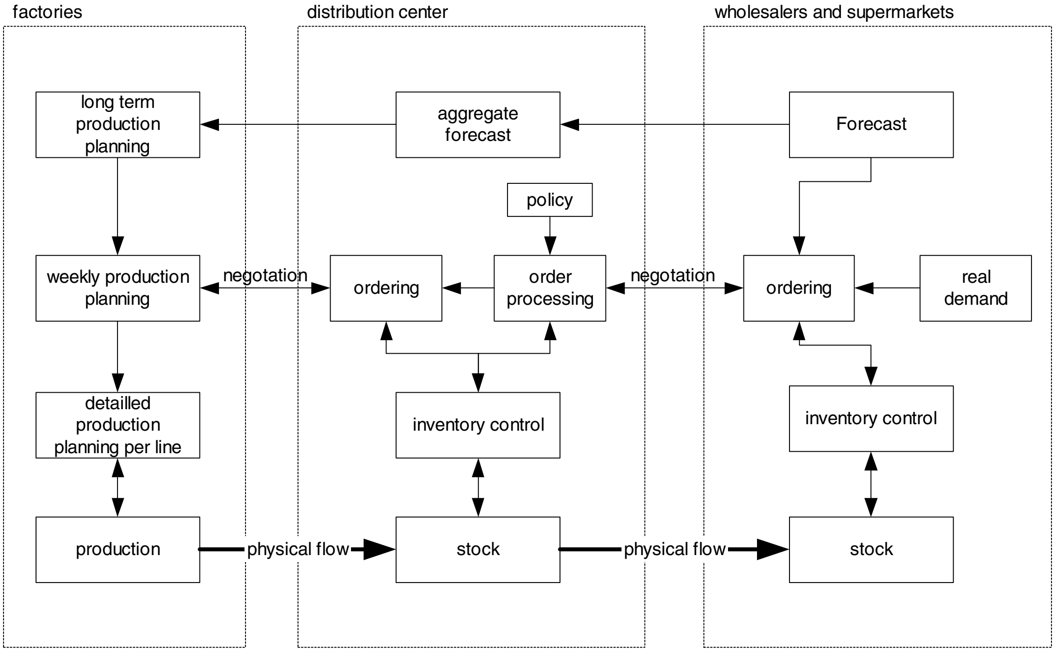

Fig. 2. The architecture of the semi-cooperative coordination model.

of intermediary or broker, as it aggregates demand from various actors, processes the demand, and negotiates both with the supply and demand to minimize the number of stock outs. The DC performs the following functions:

- Demand aggregation and processing.
- Disaggregate demand and ordering.
- Matching supply and demand.
- Optimizing supply chains by reallocating stock.
- Inventory holding to deal with fluctuation.

There are various types of functional agents, found at various hierarchical levels, including: (1) forecasting, (2) ordering and (3) execution agents. The advantage of using this vertical structure is that the different hierarchical levels can have various degrees of automation, i.e. the forecasting level can be completely handled by humans, whereas the ordering and monitoring levels can be executed be software agents operating within the constraints set at the forecasting level. This provides a way to gradually extend the number of automated agents.

The following types of agents are involved at the forecasting level:

1. *Forecasting agents* make a yearly forecast based on periods of one week.
2. *Aggregate forecasting agents* aggregate and interpret the forecasts provided by the forecasting agents. This agent checks if the forecasts take seasonal influences into account.
3. *Long-term production planning agents* reserve production capacity and provide the constraint for the weekly production planning. This involves long-term planning aimed at making long-term reservations for scarce resources based on the expected demand and determining product prices. The production planning includes the pre-production for periods with high demand like Christmas and Easter.

The ordering level concerns the real ordering within the constraints provided by the aggregate level. Order planning involves negotiations between the supply chain partners. At the ordering level the following types of agents are involved.

1. *Real demand agents* are similar to the emulation agents proposed by Julka et al. [13,14]. These agents are substitutes for customers and only exist in a simulated setting and are used to simulate the real demand based on historic information. In the implemented system, the real demand agents do not exists.
2. *Ordering agents* order products on behalf of their logistic planner. The logistic planner might directly interfere by modifying or altering decisions made by these agents. This agent negotiated with the order processing agents for gaining the right amount of products at the right time.
3. *Order processing agents* negotiate with ordering agents by assigning amounts to orders. These agents look at the actual inventory, expected replenishment(s), priority given to the ordering agent and the actual changes of stock-out of the ordering agent.
4. *The weekly production-planning agents* finalize the weekly production plan, based on the forecasted demand and actual orders. Production agents represent the factories, which have limited capacity and can only increase the capacity at high costs. Therefore, their aim is to minimize the need for extra capacity. If a factory cannot produce the demand it needs to (1) pre-produce, or (2) hire additional production capacity at extra costs or (3) add a working shift at extra costs.

The execution level controls the day-to-day operations of the physical flow.

1. *Inventory monitoring agents* take care of monitoring the inventory levels and alert ordering agents to order new products.
2. *Detailed production planning agents* represent the production lines for manufacturing products.

The horizontal coordination model incorporates more aspects of a market, or competition-based model. Agents compete with each other for the allocation of scarce inventory. The DC can be viewed as a centralized mediator balancing production capacity and product demand by keeping stock. The centralized mediator balances between optimizing the whole supply chain and taking the self-interest of actors into account. When there are conflicting interests, the main coordination function often consists of negotiation about the amount that needs to be delivered at which discrete point in time. The DC plays a crucial role, as it has the freedom to reallocate inventory reserved for one purpose to another purpose. The DC can also determine the priority that is given to an agent requesting products. An agent representing a large supermarket can be given priority over an agent representing a small or medium-sized supermarket. This aspect was viewed as a crucial element for the acceptance of the system by one large supermarket chain. In the existing situation one powerful retail chain is given priority over smaller, less powerful retail chains or single supermarkets.

The resource allocation mechanism used by the order-processing agent is depicted in Fig. 3. All orders are put in an ordering queue and prioritized. The allocation of inventory to orders is based on: (1) the inventory at the DC; (2) expected replenishment, i.e. period before the next replenishment and the number of products; and (3) priority given to the supermarket represented by the ordering agent; and (4) the actual chance of a stock-out at the supermarket represented by the ordering agent. If the inventory is high enough the desired stock is delivered. In all other situations, a proposal to order a lower amount is made. This mechanism is especially useful before and during holiday periods. This can result in a counter offer as the supermarket representing the ordering agent is running out-of-stock and other supermarkets might have more stock and therefore might demand less than initially expected.

Compared to mechanisms found in the literature, this mechanism is fairly simple and not based on any pricing system. It should be noted that in a

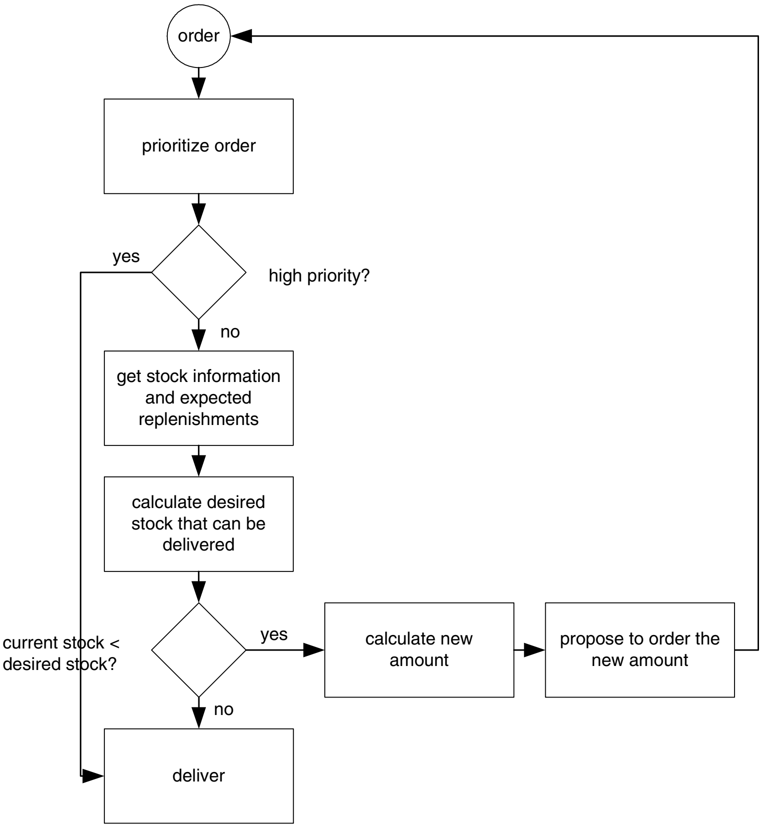

Fig. 3. The order size negotiation process.

retail chain the prices are static on the short term and are agreed on using long-term contracts often spanning many years. Consequently, the order size negotiation process tries to balance the supply and demand and avoid the number of stock outs. The mechanism is based on increasing/decreasing the ordered amount and reassigning the inventory that can be already hold on stock or is expected to arrive. This is an information intensive process and might contain multiple iterations. It is crucial that a solution is found within a short time frame, as this determines the number of stock-outs at the supermarkets.

6. Evaluation of the business value

Benefits of supply chain management systems vary and may include cost reduction flexibility, robustness, modifiability, availability, performance, lead-time, number of stock-outs and service-levels (e.g. [22,29]). We evaluated the MAS in two ways. First, a quantitative evaluation in which the situations without and with agents are simulated and compared to each other. Second, a qualitative evaluation based on the perceptions of employees of the organizations involved in the supply chain.

6.1. Quantitative evaluation

For the purpose of quantitative evaluation the participants in the design process identified a number of performance indicators. Remember that a constraint was that the number of transports should remain equal. Consequently this cannot be used as a performance indicator.

- *Total lead-time*: the time between ordering a product and receiving the product ordered.
- *Planning lead-time*: time needed for processing and preparing of an order. This excludes the physical lead-time.
- *Physical lead-time*: total time needed for loading, transportation and unloading a product.
- *Total human processing time*: total time of all human activities necessary to handle an order.
- *Stock level DC*: the average number of pallets on stock.
- The *number of stock outs*: the number of times that a dealer or supermarket is not able to sell the products demanded. This performance indicator can serve as a surrogate for customer-service levels.

The added value was assessed quantitatively by comparing the outcomes of the empirical 'as is' model with the outcomes of the 'to be' model. In the 'as is' and 'to be' models similar experiments are carried out using the same conditions and historic data. A t-test is performed with a confidence level of 5% to check whether the performance indicators listed in Table 1 are significantly better than in the current situation. The null hypothesis H_0: $\mu_1 = \mu_2$ is tested for the alternative hypothesis H_1: $\mu_1 \neq \mu_2$. The test variable is the difference between the means of both experiments. The following formula was used:

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{s_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}.$$

The distribution of t is based on $v = (n_1 + n_2 - 2)$ degrees of freedom, where

Table 1
Performance differential between the situation without and with the agent-based system

Performance indicator	Unit	Current		With agents		Absolute change	Relative change (%)	Sign?	
		Mean	SD	Mean	SD				
Total lead time	Days	15.80	0.17	12.44	0.14	3.36	21.27	Y	0.0696419
Planning lead time	Days	9.72	0.14	6.32	0.18	3.40	34.98	Y	0.072111
Physical lead time	Days	5.94	0.48	6.18	0.45	−0.24	−4.04	N	0.2080625
Total human processing time	h	0.91	0.03	0.25	0.04	0.66	72.53	Y	0.0158114
Stock level DC	#	9607.39	2.82	9288.61	2.56	318.78	3.32	Y	1.2044086
Number of stock out supermarkets	#	153.00	2.61	71.00	1.87	82.00	53.59	Y	1.0153325
Number of stock out dealers	#	57.72	0.49	36.48	0.48	21.24	36.80	Y	0.2169101

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}.$$

The value of v is rounded off to the nearest integer [20]. The null hypothesis is rejected when: $t < -t_{\alpha/2}$ or $t > t_{\alpha/2}$. The test statistic is $t_\alpha(n_1 + n_2 - 2) = t_{0.025}(18) = 2.101$. The quantifiable performance differential is shown in Table 1.

Most of the performance indicators show a better performance in the situation with the agent-based system. Only the physical lead-time does not decrease significantly. From the absolute changes of the total lead-time and planning lead-time, it can be concluded that the reduction of the lead-time is mainly caused by the reduction of planning lead-time. It is a statistical error that the planning lead-time is reduced more than the total lead-time. This difference is within the statistical error margins.

The processing time needed by human beings decreases considerably, however, is largely dependent on the behavior of the humans. This decrease considers the ideal, i.e. agents perform as many tasks as possible without any human interference. The difference in processing time reduction is less and might even show no statistically significant reduction for the situation that human planners manually handle all coordination activities.

The stock levels at the DC, supermarkets and dealers decreased significantly. Table 1 shows that the number of stock-outs decreased using the multi-agent system. When we investigate the number of stock-outs per time period, as shown in Fig. 4, it can be concluded that the system has a positive impact on the number of stock-outs during Easter and Christmas. During other periods, we did not find improved inventory levels or a decrease in the number of stock-outs.

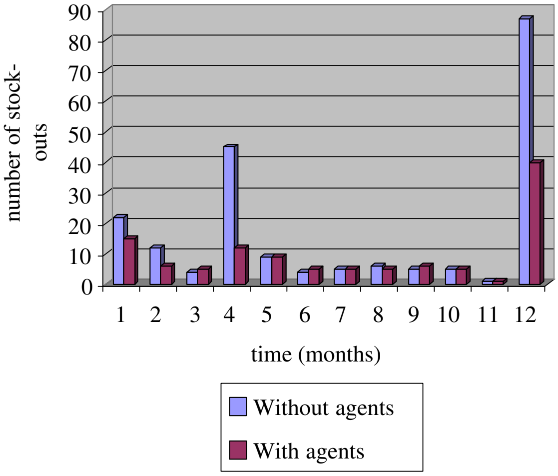

Fig. 4. Number of stock-outs per month.

6.2. Qualitative evaluation

After building the system, the model can be used to evaluate the supply chain by letting the users interact with a simulated supply chain. In this way, it can be used for supporting decision-making prior to using it in reality. The participants involved in the design process agreed unanimous over the quantitative benefits provided by the MAS. Over other advantages their opinions were more fragmented. They found the supply chain more responsiveness to changes in demand, without needing additional transports, and in this respect flexibility was created. They were not sure whether more flexibility was created for the introduction of new products. When new products were to be introduced, they were not sure whether this would require less effort with the agent-based system. Each product needs its own rules that cannot easily determined beforehand and is often determined by human planners based on their past experience.

The agents represent or assist human users in their decision-making. Agents can act proactively on behalf of users when they are offline, or having a break, sleeps, is ill, us on holiday or is not available for any other reason. This aspect was found to be especially important for small supermarkets, as they have no resources for being continually online. This ensures the continuous *availability* of a decision-maker to ensure high-responsiveness. Most of the participants found this advantage of crucial importance.

The participants found the use of a hierarchy of agents essential to the design. Within actors there is a certain hierarchy, based on coordination of the forecast, ordering and daily operations processes. This closely resembles the organizational structure, including the hierarchy of decision-making. The combination of structural and functional agents and vertical and horizontal coordination were found to be crucial concepts aligning the agent-based system to the existing organizational realities.

Between agents representing various actors a more market-like situation exists. The demand of requesting agents representing the large supermarket chain has priority over the demand of others, as the supermarket has a powerful position in the supply chain. This was a prerequisite set by the large supermarket chain for getting involved in the design of the agent-based system.

The combination of a market-oriented model and the ability to respond quickly to unpredictable demand in order to minimize stock-outs, and minimize obsolete inventory was found to be an essential benefits of the agent-based coordination model. The DC agents acting as intermediaries play a crucial role in balancing supply and demand.

From a mechanism design perspective the agent interactions and intelligence might be viewed as relatively simple. From the perspective of the stakeholders the mechanisms were viewed as sophisticated, complex and not easy to understand. More complex mechanisms, which could be able to further improve the performance, were proposed, but the participants rejected these mechanisms. This observation is in accordance with the outcomes of the experiments of Chavez et al. [4] in the business-to-consumer market. Their experiments show that people felt uncomfortable delegating a task to an agent whose behavior is complex and difficult to predict. As a result, Chavez et al. conclude that the level of sophistication may be limited more by user acceptance constraints than by limitations of available technology. The stakeholders in our case studies preferred simple, understandable mechanisms with known results over complicated mechanisms that were not easy to understand. Some of the participants viewed the agent-based system merely as a decision-support system. It should help them to identify possible bottlenecks, e.g. expected stock-outs, too high/low inventory levels, and propose possible courses of action to their logistic-planners. The planners should then decide which action should be taken and could contact logistic planners of other organization by email or phone. In this respect, the benefit that agents help people with time-consuming activities, which was already mentioned by Maes [18] in 1994 is still applicable.

7. Conclusion

Although multi-agent systems have the potential to improve supply chain management, its adoption remains limited. In this paper a semi-cooperative coordination architecture was designed and the business value was evaluated using agent-based simulation. Within the semi-cooperative architecture, agents strive to optimize the supply chain, but nevertheless try to maximize their own goals.

We developed a semi-cooperative architecture. Within the constraints of this architecture, the behavior per agent can be specified by the organizations involved. The advantage of using such a coordination model is that other agents or even human beings can substitute agents without affecting other parts. This makes a gradual expansion and adoption possible, i.e. the initial system can start with a few agents having relatively simple behavior and this might gradually be extended into a more comprehensive system. Moreover, some of the agent functionality like inventory monitoring can still be performed by the existing legacy systems as agents can be used to wrap legacy systems. Furthermore, the architecture ensures the alignment of the coordination structure with the existing organizational structure. Agents are identified with an organizational entity and the coordination architecture follows the organizational hierarchy of decision-making, by distinguishing agents at a forecasting, ordering and execution level.

In the architecture the DC played the crucial role of an intermediary or broker decoupling and aggregating supply and demand. The DC has the freedom to reallocate inventory reserved for one purpose to another purpose. The DC balances between optimizing the whole supply chain and taking the self-interest of actors into account. When there are conflicting interests, the main coordination function consists of negotiation about the amount that needs to be delivered at which discrete point in time.

The business value of agent-based systems is multidimensional and covers a large number of facets. Our case study provides evidence that a multi-agent system can deal effectively with the volatile and dynamic nature of supply chains. The simulation showed that the use of the agent-based system resulted in a reduction of the lead-time and the number of stock-outs in comparison with the current situation. The use of the agent-based system increases in some respects the flexibility of the supply chain and enables members of the supply chain to be more responsiveness to changes in demand without needing additional transports. Especially the alerting and notification of exceptions by agents, and human intervention for making decision on the logistic planning increased the responsiveness. This has a positive impact on the inventory levels and number of stock-outs during Easter and Christmas. During other periods we did not find better inventory levels or stock-outs. The agents had a profound effect on the decrease of human processing time needed of workers.

As we took the current organizational practice as a starting point and the supply chain members elicited the requirements the designed agent-system stays close to the current situation. This has advantage that the system is aligned with the organizational and it is expected that this will have a positive effect on the adoption of the agent-based system. We observed that agents representing a large supermarket can be given priority over an agent representing a small or medium-sized supermarket was crucial for adoption.

Although staying close to the organizational reality has a positive effect on the adoption, it however limits the innovativeness of the design. Consequently, some participants viewed the agent-based system primarily as a system supporting human decision-makers. The benefits are primarily obtained by making information available faster and attracting the attention of human decision-makers to negotiations and decisions that need to be taken within a short time-horizon. More efficiency gains might be accomplished by the complete handling of decision-making processes by agents. The number of decisions that will be automatically handled might gradually increase, as the users might obtain experience and get used to the system.

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